Analysis on Critical Current of Ice-melting with DC Short-Circuit for Transmission Line

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Abstract: According to the process of melting ice on conductor by short-circuit current, the basic conditions of ice-melting is analyzed in this paper. Then by analyzing the process of heat balance, a physical and mathematical model of ice-melting on critical condition is established. And then, a method to calculate the ice surface temperature and critical current is put forward, and the factors affecting critical current are analyzed. The model and methods are tested by experiment performed in artificial climate chamber, and the results of them are basically consistent with each other. Both calculation and experiment show that the ice-melting current must be greater than critical current, and should be reasonably selected according to the covered ice and the environmental conductions. The critical ice-melting current is a function of three factors including the temperature of ice surface, the diameter of conductor and the thickness of ice. It is determined by temperature of ice surface, while the later is related to the factors such as wind velocity, ice thickness, conductor diameter and environment temperature. Among them, atmosphere temperature and wind velocity are the main factors, while the influence of ice thickness is not so obvious.

Key words: DC; ice-melting; critical current; surface temperature of ice layer

NOMENCLATURE

A_c	Effective of dc current flowing (mm^2)
C_a	Air specific heat capacity (1005 J/kg °C)
D_c	Diameter of conductor (m)
D_i	Ice thickness on conductor (m)
g	Gravitational acceleration (9.8 m/s^2)
h	Heat exchange coefficient between air and ice surface (W/m^2. °C)
I	Current in conductor (A)
I_c	Critical ice-melting current (A)
J_c	Critical ice-melting current density (A/mm^2)
r_{20}, r_0	Resistance per unit length of conductor at 20°C, 0°C (Ω/m)
R_q	Thermal resistance (K/W)
T_e, ,T_i	Ambient temperature and the temperature of outer surface of ice layer (°C)
T_0	Melting point of ice (0°C)
v_a	Wind velocity (m/s)
λ_a	Thermal conductivity of air, 0.0244 W/(m°C)
λ_i	Thermal conductivity of ice, 2.22 W/(m °C)
ε	Ice surface emissivity, ε =0.95
σ	Radiation coefficient, 5.567×10^{-8} W/m^2. °C^4
μ	Air dynamic viscosity, 1.72×10^{-5} kg/(m.s)
v	Air kinematic viscosity, 1.328×10^{-5} m^2/s
ρ_a	Air density, 1.293 kg/m^3.

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I. INTRODUCTION

Ice disaster is one of the most serious threats to power system. Compared to other accidents, the losses of power grid caused by icing are much heavier. Icing can cause icing flashover, more seriously, it can cause towers (poles) failure, wires fracture and grid collapse. Prevention and control of ice disaster on transmission lines is one of the key technologies in the development of China's power grid. Although dozens of methods have been proposed to anti-icing and de-icing [1], so far, no method can prevent the ice disaster on transmission lines effectively except short-circuit ice-melting method. Because the conductor's ac inductive resistance is much larger than its dc resistance, ac ice-melting need 5~20 times larger power capacity than the one dc ice-melting need. If perform ac ice-melting on 500kV and above lines with a length over 100km, the system should supply the reactive power capacity of 1GVA~2GVA which would exceed the scope of the system can bear. So it will be harmful to the stability of system. Although the dc ice-melting needs an additional ice-melting power supply (at present, the dc ice-melting power supply will cost 400000~600000 RMB per MW),it requires less power supply than ac ice-melting because it does not need reactive power. The ice-melting radius of 60MW dc ice-melting equipment can reach to 100km. So the dc ice-melting is a simple and efficient method compared to ac ice-melting [1,2]. Especially in UHV and EHV transmission the advantage of dc ice-melting is more obvious.

The research and application of short-circuit ice-melting method have a long history. So far, rich experience of ac ice-melting has been accumulated, but dc ice-melting has not been generalized in engineering application so there is little experience about it [2]. The ice-melting of transmission line has been researched widely in the world, and many models have been proposed to calculate the ice-melting time [2], but there is relatively large error between the results calculated by existing models and the actual engineering application. The analysis shows that, the reason of the error is that all existing ac and dc models are assumed that the temperature of conductor surface be maintained at 0°C during ice-melting. But actual measurement and analysis show that temperature of conductor surface is higher than 0°C during ice-melting because of the effect of water film and air gap caused by melting ice.

The nature of ac and dc ice-melting is a process of heat exchange, so they all have a minimum ice-melting current [7-12]. In Hunan, Guizhou, and Chongqing's power grids, the ice often could not be melted from transmission lines even though the ice-melting last several hours to dozens of hours, because the relationship between the minimum ice-melting current and the environmental parameters has not been analyzed. To the best of writer's knowledge, no research has been dedicated to calculation and selection of the minimum current of ice-melting under different environments.

Aiming at the problems existed in practice of ice-melting, such as unreasonable choice of parameters etc, a physical and mathematical model of dc ice-melting is proposed in present paper based on theoretical analysis and experimental verification. The paper introduces a new calculation method of dc critical ice-melting current, and analyzes the critical current's influencing factors.

Four types of typical conductors, which have been widely used in China's power system of different voltage levels, were used as specimens to be tested and analyzed. The parameters of these conductors are shown in Tab.1.

Tab.1 Basic parameters of the conductors

Conductor type	D/mm	dc resistivity at 20°C r_{20}/(Ω/m)	dc resistivity at 0°C r_0/(Ω/m)
LGJ-70/10	13.6	0.3858×10^{-3}	0.3580×10^{-3}
LGJ-240/30	21.6	0.1085×10^{-3}	0.1007×10^{-3}
LGJ-400/35	27.6	0.07389×10^{-3}	0.0686×10^{-3}
LGJ-720/65	36.0	0.0375×10^{-3}	0.0348×10^{-3}

II. Physical and Mathematical Model of DC Critical Ice-Melting

It is assumed that the conductor is infinitely long and the icing is cylindrical and even (Fig.1). There is a preparation stage before melting ice by short circuit, the power is cut off at this stage, so the conductor temperature and the ambient temperature can be balanced, i.e. the conductor temperature, ice temperature, and ambient temperature are consistent.

Fig.1 Photo of cylindrical glaze ice on transmission line

When the current pass through the conductor, the conductor is heated by joule heat, then the heat is transferred to ice layer. When the heat is transferred to the ice surface, the temperature of ice surface rises from ambient temperature (t_e) to t_i, and then, the ice surface and air exchange the heat by convection and radiation. So, during the ice-melting, the temperature of conductor surface is the highest, the temperature gradually descends through the ice layer, and there is a temperature gradient which extend from outer surface to the enough distance in the air. At the point of this enough distance, the temperature is considered to be the ambient temperature (T_e). The temperature field is shown in Fig.2.

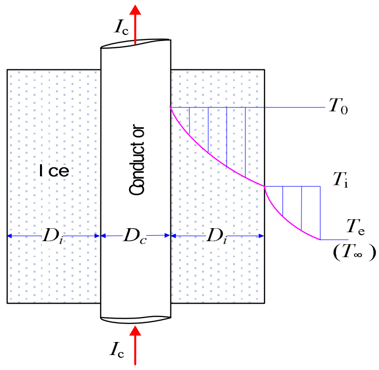


Fig.2 Temperature field on critical ice-melting state

From Fig.2, there are two heat exchange processes during ice-melting: The heat exchange occurred between conductor and ice layer, and between ice surface and air.

When the heat exchange reaches to balance, the quantity of heat exchange between ice surface and air equals to that between conductor and ice layer, and the temperature of conductor surface maintains at the melting point of ice. This is the critical ice-melting state. And the current, which maintains this state, is defined as critical ice-melting current (I_c).

If the applied current is lower than I_c, the joule heat produced by applied current could not maintain the temperature of conductor surface at 0°C, so the ice could not be melted. Therefore, when the ice-melting, the current in conductor must be larger than I_c. The paper focuses on analysis of the critical ice-melting current and its influencing factors due to the limited space. The ice-melting current in conductor is the basis for ice-melting equipment and program design, as well as for the implementation of ice-melting.

At the critical ice-melting state, the ice located on the conductor surface is not melted; the heat is transferred to ice surface, and then dissipates into the air.

Based on the basic principle of heat transfer in reference[13-20], the thermal equilibrium of dc ice-melting can be illustrated as follows:

(1) Thermal equilibrium equation of "conductor-ice" interface:

$$I_c^2 r_0 = (T_0 - T_i)/R_q \tag{1}$$

$$R_q = \frac{\ln[(2D_i + D_c)/D_c]}{2\pi k_i} \tag{2}$$

where R_q is the thermal resistance of columnar ice layer.

(2) Thermal equilibrium equation of "ice layer-air" interface:

$$I_c^2 r_0 = P_R + P_C \tag{3}$$

$$P_R = 4\pi\varepsilon\sigma(2D_i + D_c)(T_e + 273)^3(T_i - T_e) \tag{4}$$

$$P_C = \pi(2D_i + D_c)h(T_i - T_e) \tag{5}$$

where P_R is the hot loss through radiation; P_C is the hot loss through convection; h is convective heat transfer coefficient, and it can by expressed as follows [1,2-7]:

$$h = \lambda_a (Nu_n + Nu_f)/(2D_i + D_c) \tag{6}$$

$$\begin{cases} Nu_n = B(G_r \cdot P_r)^b \\ Nu_f = CR_e{}^n P_r{}^{1/3} \end{cases} \tag{7}$$

$$\begin{cases} G_r = \dfrac{g(T_i - T_e)(2D_i + D_c)^3}{v^2((T_i + T_e)/2 + 273)} \\ P_r = \mu \cdot C_a / \lambda_a \\ R_e = v_a(2D_i + D_c)(\rho_a/\mu) \end{cases} \tag{8}$$

where Nu_n, Nu_f respectively are Nusselt numbers of natural and forced convection; P_r, G_r and R_e are Prandlt number, Grashof number and Reynolds number respectively; B and b are constants determined by G_r, when the conductor icing, $1.43\times10^4 \le G_r \le 5.67\times10^8$, B=0.48, b=0.25; C, n are constants determined by Reynolds number [3]. The value of B, b, C and n are shown in Tab.2.

Tab.2 The relation between values of C, n and Re

Scope of R_e	C	n
$40 \le R_e \le 4000$	0.683	0.466
$4000 < R_e \le 40{,}000$	0.193	0.618
$40{,}000 < R_e \le 400{,}000$	0.0266	0.805

III. Critical Ice-Melting Current and Its Influencing Factors

A. Critical ice-melting current

From eqns (1) to (8), the critical ice-melting current should meet the eqns (9) to (11).

$$I_c = 3.735\sqrt{-T_i/[r_0 \ln(1 + 2D_i/D_c)]} \tag{9}$$

$$-\frac{T_i/(T_i - T_e)}{\ln(1 + 2D_i/D_c)} = \left[\frac{(T_i - T_e)(2D_i + D_c)^3}{0.525\left(\dfrac{T_i + T_e}{2} + 273\right)}\right]^{0.25} + \frac{4.766(2D_i + D_c)}{(T_e + 273)^{-3} \times 10^8} + 4.9CR_e{}^n \times 10^{-3} \tag{10}$$

$$R_e = 7.52 v_a(D_c + 2D_i) \times 10^4 \tag{11}$$

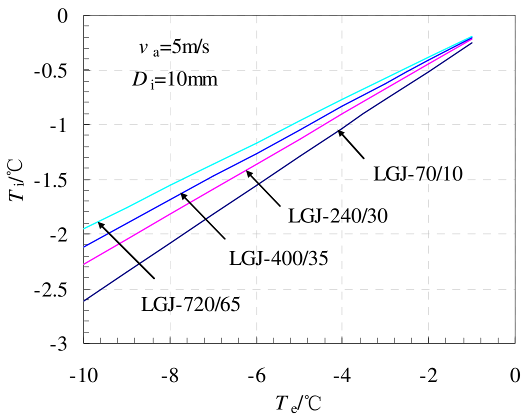
The critical ice-melting current density can be expressed as follows:

$$J_c = I_c / A_c \tag{12}$$

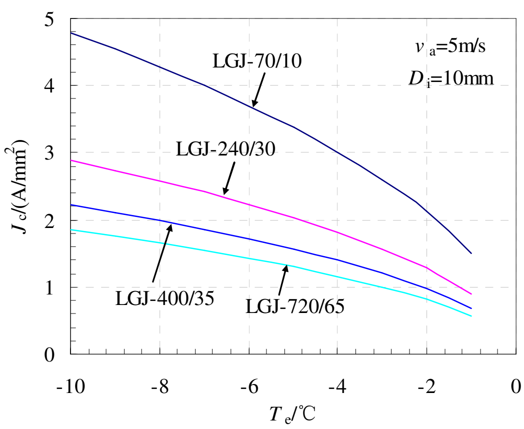
B. Factors influencing the temperature of ice surface

From eqns (9) to (11), it is known that: the critical ice-melting current is a function of conductor diameter (D_c) and ice surface temperature (T_i) as well as the ice thickness (D_i); at the critical ice-melting state the temperature of ice surface (T_i) is affected by ambient temperature (T_e), conductor diameter (D_c), ice thickness (D_i) and wind velocity (v_a). So, for the determinate conductor and ice thickness the temperature of ice surface is the key factor to determine the critical ice-melting current.

Using Matlab to solve the non-linear eqns (10) and (11), the relationship between temperature of ice surface (T_i) and ambient temperature (T_e), ice thickness (D_i) as well as wind velocity (v_a) can be obtained for the four types of typical conductors (Fig.3 to 5).



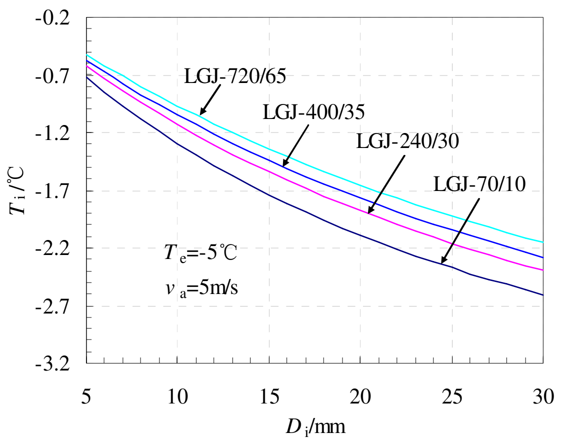
(a)



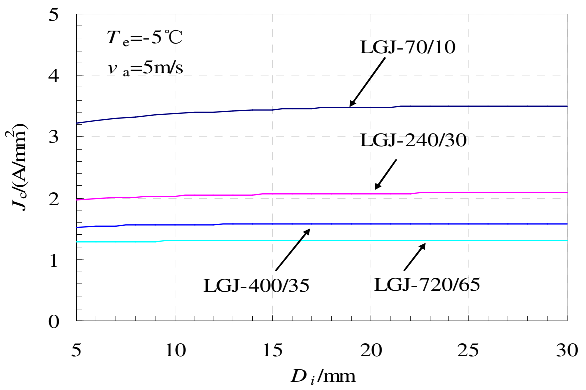
(b)

Fig.3 The influence of ambient temperature on temperature of ice surface

(a) and critical ice-melting current density (b)

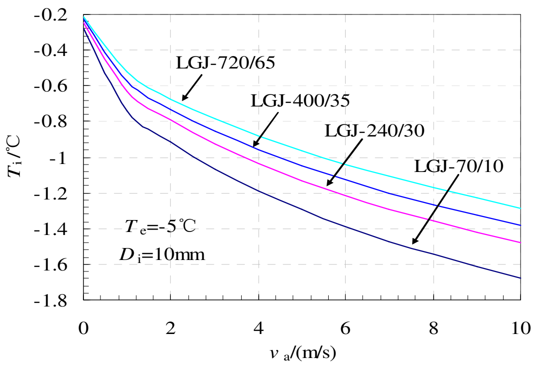


(a)

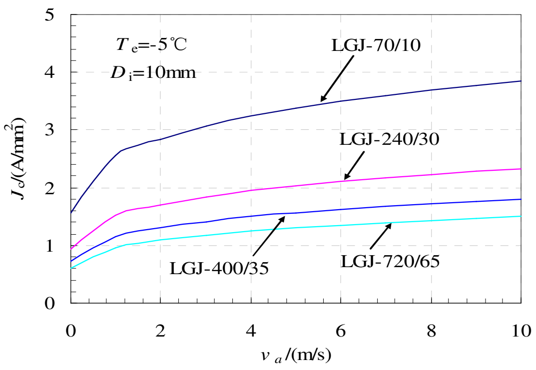


(b)

Fig.4 The influence of ice thickness on temperature of ice surface (a) and critical ice-melting current density (b)



(a) The influence of wind velocity on temperature of ice surface



(b) The influence of wind velocity on critical ice-melting current density

Fig.5 The influence of wind velocity on temperature of ice surface and critical ice-melting current density

It is known from Fig.3 to 5 that:

1) The relationship of ice surface temperature and ambient temperature is basically linear, the lower ambient temperature is, the stranger radiation and natural convection will be, consequently, the lower ambient temperature is, the larger critical ice-melting current density will be.

2) The thicker ice is, the lower ice surface temperature will be, because the thicker ice has greater thermal resistance that can impede the heat transfer to the ice surface.

3) From eqn (2), when the ice thickness is determinate, the lager conductor diameter is, the smaller thermal resistance will be, that is to say the heat is more easily transferred to ice surface, so the lager conductor diameter is, the higher ice surface temperature will be.

4) Under the condition of critical ice-melting, because there is no ice-melting, the heat of critical ice-melting current keeps the conductor surface temperature at 0°C. The heat is transferred to the ice surface and it is not consumed in the ice layer. Heat dissipation of the ice is determined by radiation and convection. In the case of constant wind velocity, the ice thickness has effect on convective heat transfer but this effect is not obviously, so the critical ice-melting current density does not increase apparently with the increase of ice thickness.

5) Wind velocity has obvious effect on ice surface temperature and critical ice-melting current density. The higher wind velocity is, the stranger forced convection will be, because more heat is taken away from ice surface by wind. So the ice surface temperature decreases and the critical ice-melting current density increases with the increase of wind velocity.

IV. Experimental Verification

In order to verify the correctness of eqns (9) to (11), the experiment was carried out in multi-function artificial climate chamber with a diameter of 7.8m and a height of 11.6m. The dc ice-melting power supply can provide current as high as 5000A. The test conductors was 80m long, and it was wound spirally on a tripod. The temperature of conductor surface and ice surface were measured by DS18B20 temperature sensor produced by

DALLAS Company. Its measuring range of temperature is -55°C~+125°C and its accuracy is ±0.5°C. The arrangement of specimen and the test circuit are shown as Fig. 6 and 7. The verification results are shown in Tab.3.

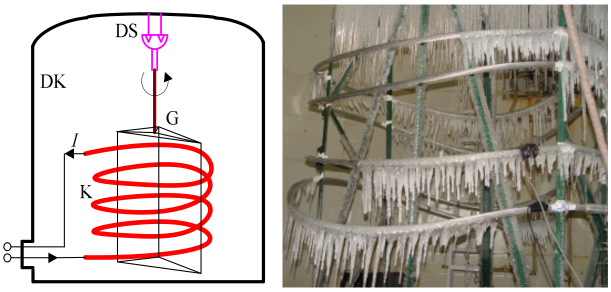


Fig.6 Sketch of short- circuit melting ice in the artificial climate chamber (DK: artificial climate chamber; DS: Rotating electric hoist; G: sample rack; K: sample conductor)

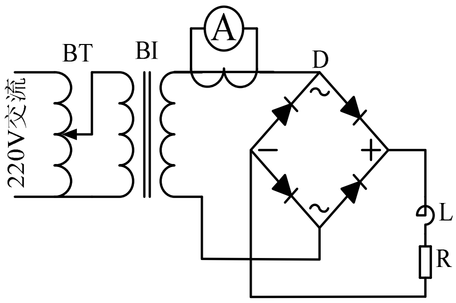


Fig.7 Experiment circuit (D: Bridge rectifier; L: smoothing Reactor; R: sample Resistance; BT: Regulator; BI: Transformer)

Tab.3 Verifying the critical ice surface temperature and critical current of ice-melting

type	d	t_e	v_a	t_i/°C		I_c/A	
	mm	°C	m/s	Measure-ment results	Calcul-ation results	Measure-ment results	Calcul-ation results
70/10	10	-1	3	-0.2	-0.21	100	95
	15	-3	1	-0.7	-0.61	150	143
	10	-5	5	-1.5	-1.29	250	236
240/30	15	-3	1	-1.0	-0.53	300	290
	25	-5	3	-2.0	-1.86	480	464
	10	-5	5	-1.2	-1.13	490	489
400/50	20	-5	1	-1.2	-1.06	500	491
	10	-3	3	-0.5	-0.51	480	436
	10	-5	5	-1.0	-1.05	600	626
720/65	15	-1	3	-0.2	-0.22	400	379
	15	-3	3	-0.8	-0.66	700	662
	10	-5	5	-1.1	-0.97	1000	937
	5	-3	1	-0.2	-0.16	520	511

From Tab.3, the absolute error of ice surface temperature between the calculation results and measurement results is 2.0%~20%, and the critical ice-melting current's absolute error is 0.1%~10%. The critical ice-melting current's absolute error is relatively small while the ice surface's is relatively large because the measurement error of the ice surface temperature is large.

V. Conclusions

(1) There is a critical current in dc short-circuit ice-melting method. Only when the ice-melting current is larger than the critical current, can the ice on transmission lines be melted effectively. So, when the dc short-circuit method is used to melt ice, the ice-melting device should be designed reasonably.

(2) The critical ice-melting current related to the conductor diameter, ambient temperature, and wind velocity as well as ice thickness. The critical current will be different under different condition. The relationship between critical current and ice thickness is not obvious.

(3) The calculation method of critical current proposed in the paper, which has been validated by test, can be used to calculate and analyze the critical ice-melting condition.

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